Influence of discharge tube wall thickness on surface-wave discharge parameters

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We showed that the attenuation characteristics of discharge sustained in dielectric tubes by the surface wave depend on thickness of the tube wall. In consequence, the axial distribution of the linear power density absorbed in plasma also depends on the wall thickness. The plasma column length versus the absorbed microwave power can be approximated by a power function. According to our theoretical predictions the plasma column is longer in the discharge tube of smaller outer radius, for a given value of the absorbed microwave power. The theoretical results are in agreement with the results of an experiment we carried out using a surfaguide to sustain surface-wave discharges in neon and argon at atmospheric pressure.

1. Introduction

In recent years, an increased interest has been observed in atmospheric pressure surface-wave discharges (SWDs). Both experimental [1-3] and theoretical [4-7] works on SWDs sustained in dielectric tubes have been published lately. The renewed interest is due to actual and possible applications of SWDs, which are spectrochemical analysis, surface treatment, diamond deposition, sterilization, purification of noble gases and destruction of contaminant gases.

In SWDs, the electromagnetic wave and plasma mutually interact. The plasma is sustained by the electric field of the wave, being an essential part of the guiding structure, which enables the wave to propagate. The plasma parameters affect the wave propagation and the wave characteristics determine plasma parameters. It should be noticed that propagation of the wave depends not only on parameters of the plasma itself but also on properties of other parts of the wave-guiding structure containing the plasma.

It is well known that SWD properties strongly depend on the value of the internal radius of discharge tube, and hence the plasma column radius. In particular, the average electron number density increases if the radius decreases. However, other parameters of the wave guiding structure (e.g. the wall thickness and the electric permittivity of discharge tube or a presence of cooling and/or screening systems) also affect the wave propagation and therefore discharge parameters.

That fact is not always taken into account. In some experimental works such parameters as the outer radius of discharge tube or dimensions of additional tube with cooling liquid are not given. This makes comparison of the experimental and numerical results difficult.

It is the aim of this work to examine how the tube wall thickness (or equivalently, the tube outer radius) affects attenuation characteristics of surface wave and, in consequence, other discharge parameters.

2. Influence of the discharge tube wall thickness on surface wave propagation

To examine the influence of the tube wall thickness, let us consider the propagation of an electromagnetic wave along a uniform plasma column surrounded by a discharge tube of the inner radius a and outer radius b as shown in Fig. 1. The relative permittivity of discharge tube material is ε_d. The tube is placed along the z axis of a cylindrical co-ordinate system. We treat the plasma as a dielectric medium with the relative electric permittivity ε_p. The value of ε_p, which depends on the electron number density n_e and electron collision frequency for momentum transfer ν is given by the Lorenz formula

$$\varepsilon_p = 1 - \frac{n}{1 - is}, \quad (1)$$

where $i = \sqrt{-1}$, $n = n_e/n_c$ and $s = \nu/\omega$ are the

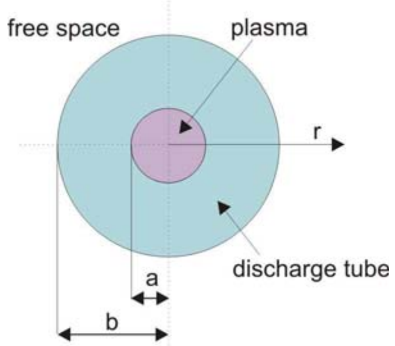

Fig. 1. Cross section of wave-guiding structure.

normalized electron number density and normalized collision frequency, respectively, ω is the angular field frequency. The value n_c is the critical electron density

$$n_c = \omega^2 \varepsilon_0 m / e^2 , \qquad (2)$$

where ε_0 is the electric permittivity of free space, e and m are the electron charge and mass, respectively.

The electric and magnetic fields of the surface wave can be found from the wave equation. The azimuthally symmetric solution of the wave equation for the axial component of electric field E_z has the form:

$$E_{z,i} = [A_i I_0(\gamma_i r) + B_i K_0(\gamma_i r)] \exp(-\gamma z) \qquad (3)$$

with

$$\gamma_i^2 = \left(\gamma^2 + \beta_0^2 \varepsilon_i\right), \qquad (4)$$

where $\gamma = \alpha + i\beta$ is the wave propagation coefficient, α and β are the attenuation and phase coefficients, respectively, β_0 is the free-space phase coefficient, I_0 and K_0 are the modified Bessel functions of order zero, the indices $i = 1, 2, 3$ correspond to the plasma, discharge tube and free space, respectively, (Fig.1).

The attenuation and phase coefficients can be determined from the wave dispersion equation, which can be symbolically written as

$$D(\gamma, \omega, a, b, \varepsilon_i) = 0. \qquad (5)$$

The dispersion equation (5) is obtained from the continuity conditions of the tangential electric and magnetic field components at the interfaces of the two media, for $r = a$ and $r = b$.

Numerical calculations of the propagation coefficient (α and β) were performed for the following data: the inner radius of the tube $a = 1$ mm, the wave frequency $f = \omega/2\pi = 2.45$ GHz, the relative electric permittivity of the dielectric tube $\varepsilon_d = 3.78$ (quartz) and the normalized electron frequency $s = 2$, which is typical for high pressure gas discharges. Fig. 2 shows the normalized attenuation characteristics αa for different values of outer radius b of the discharge tube. For constant value of b, the coefficient α monotonically decreases with increasing the normalized electron density n. Fig. 3 presents the influence of the tube outer radius b on the normalized attenuation αa and phase coefficients $\beta/\beta_0$for a constant value of n. For the constant value of n the coefficient β increases monotonically with increasing the tube wall thickness from β_0 to $\beta_0\sqrt{\varepsilon_d}$. In consequence, the wavelength $\lambda = 2\pi/\beta$ decreases by a factor about 2. The coefficient α increases about 3 times with increasing the outer radius of the tube b from 1 mm to about 10 mm. With further increase of the radius b, the coefficient α decreases to a constant value.

Radial distributions of the electric field axial component E_z for different values of the radius b are shown in Fig. 4. It is seen that for all values of b the distributions of E_z in the plasma are identical, while they differ outside the plasma (in the discharge tube and free space). This is a reason why the attenuation coefficients α for different values of b differ as well.

3. Influence of the discharge tube wall thickness on parameters of atmospheric pressure SWD

The discharge parameters depend on plasma and surface wave properties, so they should be determined in a self-consistent way. Such models

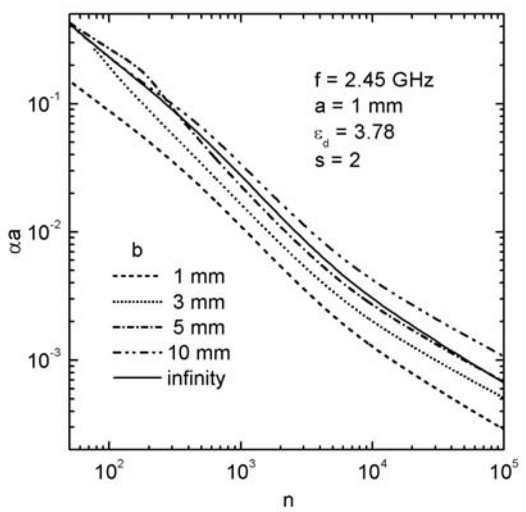

Fig. 2. Normalized attenuation αa vs. the normalized electron concentration n, for various values of the discharge tube outer radius b.

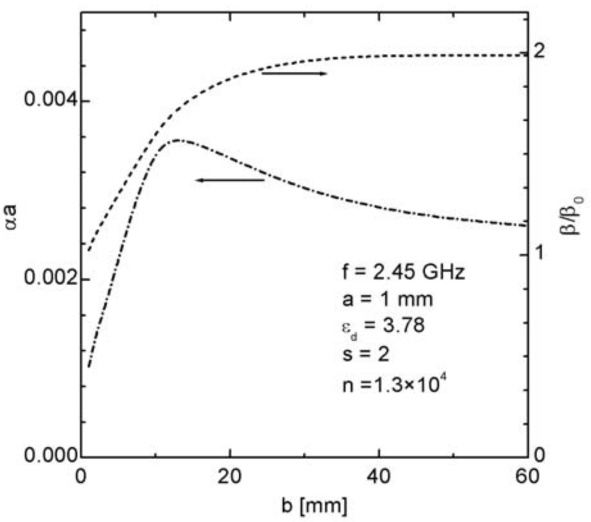

Fig. 3. The normalized attenuation αa and normalized phase β/β_0 coefficients vs. the discharge tube outer radius b, for constant values of n and s.

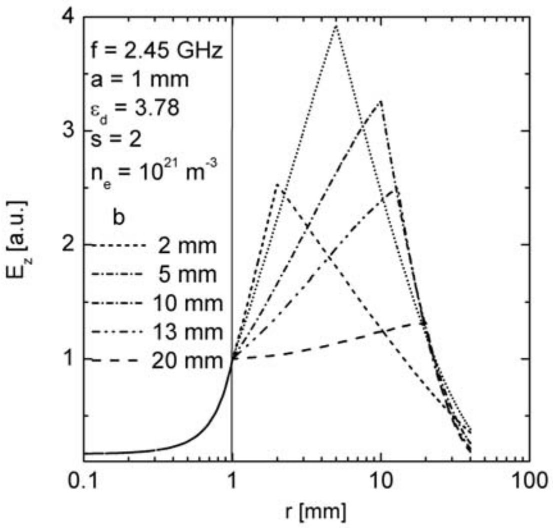

Fig. 4. Radial distribution of the axial component of the electric field E_z for different values of *b*.

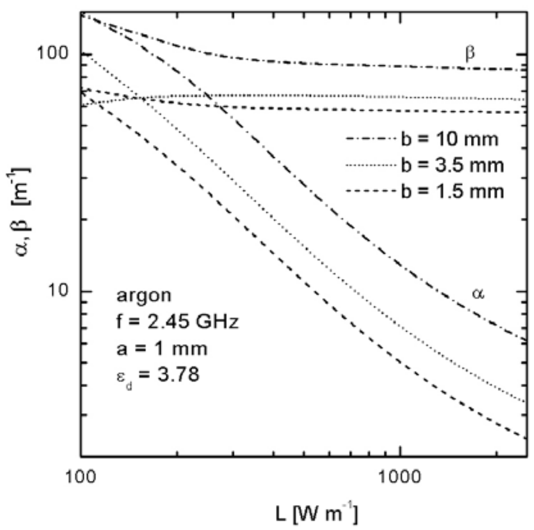

Fig. 5. Attenuation α and phase *b* coefficients as functions of *L* for various values of *b*.

that enable to obtain the spatial distributions of discharge parameters as well as the wave characteristics were presented for SWDs in argon [7] and neon [8]. These models used the *local axial uniformity approximation* [9] and an assumption that the radial distributions of discharge parameters depend only on *L* (the linear power density absorbed in the plasma). The axial distribution of $L(z)$ can be found from [9]:

$$\frac{\mathrm{d}L(z)}{\mathrm{d}z} = \frac{-2\alpha(L)L(z)}{1-\dfrac{L}{\alpha}\dfrac{\mathrm{d}\alpha(L)}{\mathrm{d}L}}. \qquad (6)$$

Merging radial distributions of plasma parameters for a given *L* with the calculated $L(z)$ provides the spatial distribution of the parameters. It is seen from eq. (6) that the wave attenuation characteristics $\alpha(L)$ plays the crucial role in the model, because it constitutes a link between the radial and axial distributions of plasma parameters.

We applied the model presented in [7] to determine the wave propagation characteristics for SWD sustained in argon at atmospheric pressure.

Fig. 5 shows propagation characteristics $\alpha(L)$ and $\beta(L)$ for three discharge tubes of different outer radii. It is seen, that for each tube the coefficient α decrease monotonically with *L*, while β is almost constant. The values of both α and β increase with increasing outer radius. We found that $\alpha(L)$ in log-log scale can be approximated by a straight line, which means that it can be expressed in the form:

$$\alpha(L) = pL^{-q}, \qquad (7)$$

where *p* and *q* are real numbers and $p, q > 0$. From Fig. 5, it is seen that if *b* increases, the value of *p* also increases, while *q* almost does not change. The same type of dependence we obtained also for SWD in neon at atmospheric pressure, using model [8].

After simple transformations of eq. (6) and (7), one can obtain the analytical expression for the axial distribution of $L(z)$

$$L(z) = \left(\frac{2pq}{1+q}\right)^{1/q} (-z)^{1/q}, \qquad (8)$$

and for the axial distribution of the power flux $P(z)$

$$P(z) = (2p)^{1/q}\left(\frac{q}{1+q}\right)^{(1+q)/q} (-z)^{(1+q)/q} \qquad (9)$$

together with the length of the plasma column *d*

$$d(P_0) = (2p)^{-1/(1+q)}\left(\frac{q}{1+q}\right) P_0^{\,q/(1+q)}, \qquad (10)$$

where P_0 is the power flux at the beginning of the plasma column. We assumed here that the plasma column ends in the $z = 0$ plane, where $L = 0$ and that *L* and *P* are linked by relation $2\alpha(L)L(z) = P(z)$.

It follows from eq. (8) and Fig. 5 that the axial distribution $L(z)$ depends on the value of *b*, so do other plasma parameters, which are related to *L*.

From eq. (10), it can be seen that the length of the plasma column *d* is a power function of P_0, with the exponent depending solely on *q*. It means that the dependence $d(P_0)$ in the log-log scale is linear, but the slope of the line does not depend on *b*. One can also find from Fig. 5 that increasing *b* (from 1.5 to 10 mm) shortens the plasma column.

4. Comparison between experimental results and calculations

We carried out an experiment to compare our theoretical predictions with experimental. For generation of SWDs we used a surfaguide. The

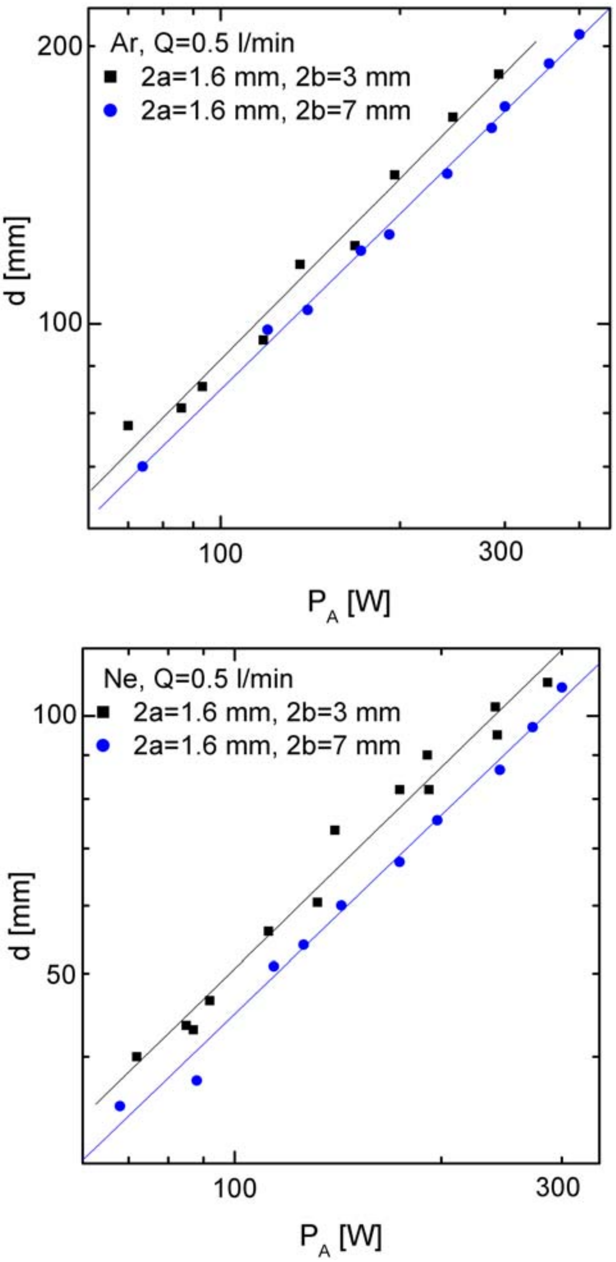

Fig.6. The dependence of the average plasma column length on absorbed microwave power for discharge in (a) argon and (b) neon. The experimental results (points) are approximated by straight lines.

details of the setup are described in [9]. We used two quartz discharge tubes, with the same inner radius (0.8 mm) and two different outer radii (1.5 mm and 3.5 mm). The working gases were argon and neon at atmospheric pressure with a flow rate of $Q = 0.5$ l/min. Two plasma columns (upstream and downstream) are sustained if the surfaguide is used [7]. The columns lengths are almost the same if the gas flow intensity is low.

Figs. 6a and 6b show the average plasma column lengths d versus the absorbed microwave power P_A for SWDs in argon and neon, respectively. In all cases, the plasma column length increases with increasing the absorbed microwave power. The presented dependences are linear in log-log scale. The slopes of the lines are almost the same for different outer radii, both in argon and neon. For a given value of P_A, the plasma column length is longer for discharge in the tube of smaller outer radius. These experimental results are in accordance with our theoretical predictions presented in sec. 3.

4. Conclusion

We have shown that the attenuation characteristics of discharges sustained in dielectric tubes by surface wave depend on thickness of the discharge tube wall. In consequence, the axial distribution of the linear power density absorbed in the plasma also depend on the wall thickness. The plasma column length versus the absorbed microwave power can be approximated by a power function. According to our theoretical results, for a given value of the absorbed microwave power P_A, the plasma column is longer in the discharge tube of smaller inner diameter. The experimental results confirm the theoretical predictions.

5. References

[1] Y. Kabouzi, M.D. Calzada, M. Moisan, K.C. Tran, C. Trassy, J. Appl. Phys. **91** (2002) 1008.

[2] A. Sainz, M.C. Garcia, M.D. Calzada: 32 ESP Conf. Plasma Phys. Tarragona ECA 29C (2005), 4.132 and 4.133.

[3] M. Jasiński, Z. Zakrzewski, J. Mizeraczyk, Czech. J. Phys. **56** (2006) B787.

[4] M.S. Benilov, G.V.Naidis, IEEE Trans. on Plasma Science **31** (2003) 488.

[5] E. Castaños-Martínez, Y. Kabouzi, K Makasheva, M. Moisan, Phys. Rev. E **70** (2004) 066405.

[6] Y. Kabouzi, D.B. Graves, E. Castaños-Martínez, M. Moisan, Phys. Rev. E **75** (2007), 016402.

[7] H. Nowakowska, D. Czylkowski, Z. Zakrzewski, J. Opt. Adv. Mat. **7** (2005) 2427.

[8] H. Nowakowska, M. Jasiński, J. Mizeraczyk, Z. Zakrzewski, Y. Kabouzi, E. Castaños-Martinez, M. Moisan, Czech. J. Phys. **56** (2006) B964.

[9] Z. Zakrzewski, M. Moisan, Plasma Sources Sci. Technol. **4** (1995) 379.

[10] D. Czylkowski, M. Jasiński, J. Mizeraczyk, Z. Zakrzewski, Czech. J. Phys. **56** (2006) B684.